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Fan Noise Reduction Achieved by Removing Tip Flow Irregularities Behind the Rotor—Forward Arc Test Configuration

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FAN NOISE REDUCTION ACHIEVED BY REMOVING TIP FLOW

IRREGULARITIES BEHIND THE ROTOR -

FORWARD ARC TEST CONFIGURATION

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SUMMARY

An investigation was conducted to study the noise source caused by the interaction of the rotor tip flow irregularities (vortices and velocity defects) with the downstream stator vanes. Fan flow was removed behind a 0.508 meter (20 in.) diameter model turbofan through an outer wall slot between the rotor and stator. Noise measurements were made with far-field microphones positioned in an arc about the fan inlet and with a pressure transducer in the duct behind the stator. Little tone noise reduction was observed in the forward arc during flow removal; possibly because the rotor-stator interaction noise did not propagate upstream through the rotor. Noise reductions were measured in the duct behind the stator and the largest decrease occurred with the first increment of flow removal. This result indicates that the rotor tip flow irregularity-stator interaction may be as important a noise producing mechanism as the normally considered rotor wake-stator interaction.

INTRODUCTION

One of the major noise producing mechanisms in a fan stage for a turbofan engine is the interaction of the rotor wakes with the downstream stator vanes. A previous paper (ref. 1), indicated that the rotor tip flow irregularities (vortex and velocity defects) may be as large as or larger than the mean rotor wake as a source of tone noise. In order to investigate this possibility, a fan stage model was modified by placing a slot in the outside fan casing between the rotor and stator to draw off the rotor tip vortex and velocity defects before they reached the stator vanes. The intent of the experiments was to measure both the forward and rear arc noise reductions in the Lewis fan and jet noise test facility pictured in figure 1 (forward arc configuration). This paper presents the results of the experiment performed in the forward arc configuration. A measure of the aft propagating noise was also obtained using a wall mounted pressure transducer located downstream of the stators.

APPARATUS AND PROCEDURE

Fan and test facility. - The experiments were performed in the Lewis engine fan and jet noise facility, that has been described in detail in reference 2. Figure 1 shows a fan with a modified flight type inlet installed in

the facility and also some of the microphones used for far-field noise measurements. Plan and elevation views of the facility are shown in figure 2. The configuration shown in figure 2 is the forward arc configuration with air entering the room through the silencer and with the fan discharging into a collector in the motor drive room and then through two exhaust ducts to the atmosphere above the building. The facility has an array of fixed far-field microphones on a 7.6 meter (25 ft) radius centered at the fan inlet face. These are positioned at 10° intervals from 0° to 90° from the fan inlet axis. In addition a pressure transducer was installed in the fan exhaust duct, behind the stators, for some of the testing.

Two different inlet assemblies were used for these experiments. The one configuration was with an inlet having flight-type internal contours and thick lip, which was essentially the same as that used in references 2 and 3. The other configuration tested used the same inlet with the addition of the turbulence-reducing inlet flow control device (ICD no. 1) shown in figure 3. This inlet control device was tested previously in references 3 and 4 and was successful in reducing blade passage tone noise caused by inlet flow disturbances.

The fan used in this testing was 0.508 meters (20 in.) in diameter and was designed QF-13. Noise data from this fan were reported previously in reference 4. The design characteristics of this fan are shown in table I and more information can be found in reference 4. The fan as shown in figures 4 and 5 has 40 rotor blades and 45 stator vanes and the design rotor tip relative Mach number is 1.647 which yields a supersonic rotor tip for conditions above 60 percent design speed. To investigate the effect on the fan blade passage tone, test points where the tone was clearly visible were emphasized. These conditions were at 70 percent speed and below since the multiple pure tones at the higher speeds appeared to dominate the spectrum (see fig. 10, ref. 4). Acoustic data were taken with the fan operating at 50, 60, 70, 80, 90, and 95 percent design speed by the far-field microphones and the aft transducer tests were performed at 50, 60, and 70 percent design speed.

<u>Flow removal apparatus</u>. - A circumferential slot on the outside wall was used to remove the flow between the rotor and the stator. This slot was approximately 1.27 cm (1/2 in.) wide and connected to a plenum chamber outside the fan package (see fig. 6). The plenum chamber was connected by four hoses to an exhaust system. A photograph of the outside of the plenum chamber and the four connecting hoses is shown in figure 7. During testing, the plenum and hoses are behind the acoustic wedges which surround the fan inlet (see fig. 1).

The exhaust system which removes the rotor tip flow is controlled by a butterfly valve operated in a manner to remove a fixed percentage of the fan flow. The flow removal experiments were performed to keep the total flow through the fan rotor constant. This was done by closing down the valves controlling the main fan exhaust flow to balance the flow removed through the slot. The original intent was to remove flow through the slot in roughly 2.5 percent increments starting at 2.5 percent of the total flow and going up to the maximum flow of the exhaust system. At design conditions (100 percent speed) this maximum would be around 10 percent of the total flow and at lower speeds would represent a higher percent flow. During the initial testing of

the device it was found that a flow instability existed in the removal equipment such that at flows below 1.3 kg/sec (2.8 lb/sec) testing was not possible. At 50 percent speed this represented roughly 7 percent of the fan flow. Therefore the experiments were performed from 7.5 percent of flow in steps of 2.5 percent until the flow limit of the exhaust system was reached. Table II gives a matrix of the conditions tested. This table also shows which test points had microphones only and which also had the exhaust pressure transducer in place.

The microphone and pressure transducer data were processed on line with a narrowband analyzer with a 0 to 20 000 Hz range at 50 Hz bandwidth. At 50, 60, and 70 percent speeds the blade passage tone and the tone at twice blade passage frequency could be read from these spectra while at higher speeds only the blade passage tone could be read. Simultaneously with this on line analysis, the microphone and transducer signals were recorded on magnetic tape for future analysis as desired.

RESULTS AND DISCUSSION

In general, it would be expected that as more of the tip flow was removed between the rotor and stator that the tone noise due to rotor-stator interaction would be reduced. If the rotor wakes were uniform from hub to tip, this reduction would be expected to be about 20 $\log_{10}$ (1-X), where X is the fraction of flow removed (ref. 1). If, as was postulated in reference 1, the region near the tip produced a proportionally larger noise than other regions, the first increments of flow removal would produce larger reductions than the 20 $\log_{10}$ variation mentioned above. A noise reduction larger than that expected from uniform wake variation, was then the result which would point toward the tip region as a major noise contributor.

Far-field Forward Arc Noise

The blade passage tone noise measured by the far-field microphones showed virtually no noise reduction when flow as removed between the rotor and the stator. An example of this can be seen in figure 8 at 50 percent speed which is the data with the ICD in place. Not all of the percentage flow points are shown here because of crowding but the entire range from zero to 20 percent flow removal is represented. The no flow data were taken with the slot in place. Comparisons, on a 1/3 octave basis, of the no flow tones from this data and the previous data without a slot, reference 4, showed that the slot did not add forward arc tone noise. As can be seen from this figure no consistent noise reduction was observed at the far-field microphones. The apparent lack of even the noise reduction expected from uniform wake removal probably indicates that the forward arc blade passage tone was not controlled by the rotor-stator interaction, even with the ICD in place. It is possible that the noise generated on the stator vanes as a result of the rotor wake interaction is not able to propagate upstream through the rotor due to the high subsonic rotor tip speed and the direction of sound propagation relative to the channels formed by the rotor blades. A discussion of this can be found in reference 5 and appears to be the case here since even the general trend with flow removal is not observed.

Analysis of the 2xBPF tone showed this same general lack of effect except at 50 percent speed, where a weak effect was observed at some angles. A plot of the data is shown in figure 9 where a reduction is seen with increasing removal flow. The largest differential reduction occurs with the first 7.5 percent of flow removed. This reduction is particularly apparent at the 40 to 60 degree positions where it appears that lobes in the directivity pattern have been removed.

The relatively large effect on the harmonic, when none was apparent in the primary tone, may indicate that the forward-arc harmonic was controlled by the rotor-stator interaction noise while the blade passage tone was not. Perhaps this is because the harmonic noise pattern passes more easily through the rotor. The strength of the rotor-stator caused harmonic may also be larger than the rotor-stator interaction caused blade passage tone as a result of the wake pattern behind the rotor. Instead of a single blade wake which might be stronger near the tip because of tip vortices and velocity defects, etc. some recent measurements of the wake of a turbofan rotor near the tip have indicated that two regions of velocity defect may be present behind each blade (ref. 6). One defect comes from the typical rotor wake and the other from he tip flow irregularities. This dual pattern could result in a strong 2xBPF tone generated on the stator which is not completely removed by transmission through the rotor.

In general, the blade passage tone data in the forward arc did not show a large noise reduction with the first increment of tip flow removal as needed to verify the hypothesis of a strong tip noise source. In fact, they showed very little noise reduction with any flow removal. This indicates that the forward-arc microphones may not be seeing the rotor-stator interaction noise, possibly a result of the noise not propagating upstream through the rotor (ref. 5).

In Duct Transducer - Behind Stator

To observe if any effect of the flow removal might be measured in the aft radiated noise, a single pressure transducer was installed 7.6 cm (3 in.) behind the stators at roughly the 10 degree position (measured clockwise looking into the fan inlet). Experiments were performed at 50, 60, and 70 percent design speed with flow removal varying from 0 to 20 percent of fan flow. (See table II). The noise measured at this transducer location showed a considerable effect of flow removal. Figure 10 is a plot of the reduction in blade passage tone versus percent flow removal for the 50, 60, and 70 percent speeds. As can be observed, blade passage tone noise reductions occurred for all of the flow conditions tested. Shown also on the plots is a solid line which is the noise reduction that would be expected if the rotor wake were uniform from hub to tip. This curve is based on 20 $\log_{10}(1-X)$. The data all show more reduction than postulated by the solid curve. This additional reduction may be an indication that the tip region produces more noise than would be expected for a spanwise uniform wake. To get an indication of the amount of this extra tip noise, the uniform wake reduction curves were translated on the plots so they went approximately through the measured data. These are the dashed lines in figure 10. The dashed lines fit the data fairly well, particularly at 50 percent and 60 percent speeds and are extrapolated back to the 0 percent axis to indicate a uniform wake noise reduction. The

offset measured at the 0 percent axis is then an indication of the extra noise generated near the tip. This seems to be somewhere between 2 dB at 70 percent speed and 4 dB at 50 percent speed. The existence of this offset suggests that the interaction of the rotor tip flow irregularities (vortices and velocity defects) with the stator vanes is a significant fan noise mechanism. The actual noise reduction curve shape between the 0 percent flow removal and the 7.5 percent removal points is not known from this data. A smooth curve might be expected having a sharp noise reduction while the tip flow irregularities are being removed and then blending into the 20 log (1-X) curve at the 7.5 percent flow removal point.

Reductions in the tone at twice blade passage frequency can be seen in figure 11. An offset is observed for the 60 percent speed case and the 70 percent case shows reductions larger than expected for the uniform wake. This supports the significance of the rotor tip flow irregularity-stator interaction as a noise source. The reason for the apparent lack of an offset for the 50 percent speed case is not accurately known at this time but is probably related to the fact that this was the only case which showed an effect in the forward arc (fig. 9).

The noise measurements obtained in the aft duct were obtained with a single pressure transducer and are not measurements of the total sound power radiated to the rear of the fan. Therefore, experiments with the fan exhausting into the room are being planned so that an array of microphones can more accurately measure the rear arc noise with flow removal.

CONCLUDING REMARKS

Noise data were taken as various amounts of flow were removed through an outer wall slot located between the rotor and stator of an existing fan stage. Data taken with far-field microphones in an inlet arc showed little tone noise reduction with increased flow removal; possibly because the rotor-stator interaction noise does not propagate upstream through the rotor for this particular fan.

A pressure transducer was installed in the aft duct behind the stator and showed considerable tone noise reduction with increased flow removal. These data indicated that proportionally more noise reduction was achieved with the first increment of flow removed than with subsequent increments. This result then points to the possibility that interaction of the tip region flows (vortex and velocity defects) with the downstream stators is as large a noise producing mechanism as the normally considered rotor wake-stator interaction mechanism.

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TABLE I. - QF-13 FAN DESIGN CHARACTERISTICS

Total pressure ratio	1.500
Rotor-tip diameter, m (in.)	0.508 (20.0)
Tip speed, m/sec (ft/sec)	487.7 (1600)
Hub-tip radius ratio	0.46
Stage adiabatic efficiency	0.88
Total flow, kg/sec (lb/sec)	32.5 (71.7)
Inlet specific flow, kg/sec/m^2 (lb/sec/ft^2)	205.1 (42.0)
Number of rotor blades	40
Number of stator vanes	45
Rotor-tip inlet relative Mach number	1.647
Shaft speed, rpm	18 366
Rotor blade passage frequency, Hz	12 244

TABLE II. - TEST CONDITIONS

Percent speed	Percent removal flow					
	0	7.5	10.0	12.5	15	20
50 open inlet	X 0	X 0	X 0	X 0	X 0	X 0
ICD	X	X	X	X	X	X
60 open inlet	X 0	X 0	X 0	0	X 0	X[1] 0[1]
ICD	X	X	X	X	X	X[1]
70 open inlet	X 0	X 0	X	0	X	
ICD	X	X	X	X	X	
80 open inlet	X	X	X		X[2]	
ICD	X	X	X	X	X[3]	
90 open inlet	X	X	X	X		
ICD	X	X	X	X		
95 open inlet	X	X	X	X[4]		
ICD	X	X	X	X		

Blank	Not tested
X	Far-field inlet arc microphones
0	Aft duct pressure transducer
1	Actually 19 percent flow
2	Actually 14.7 percent flow
3	Actually 14.3 percent flow
4	Actually 12.3 percent flow

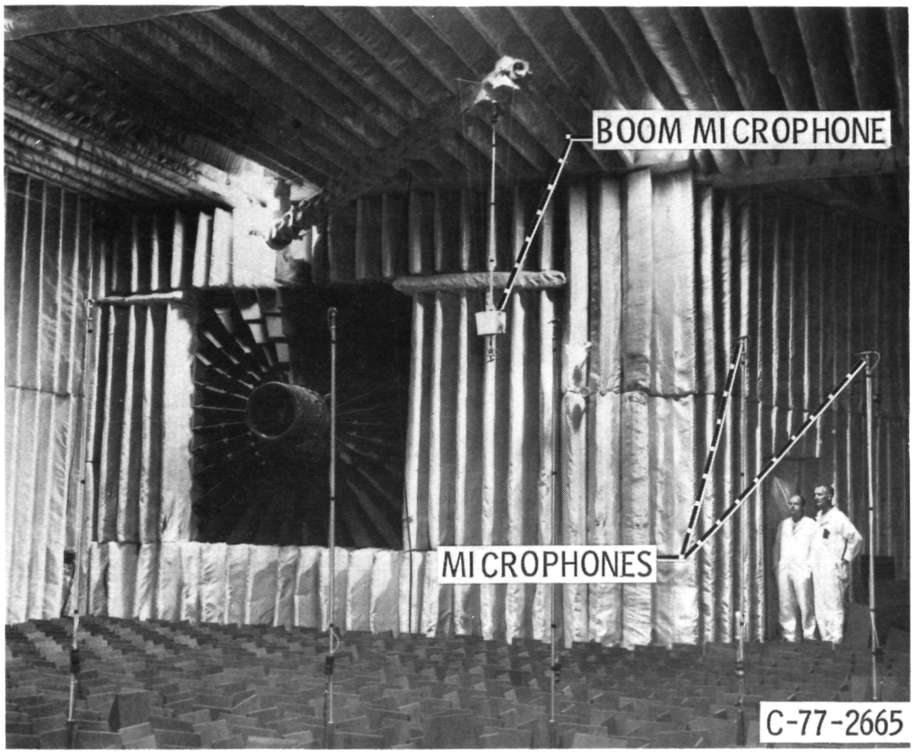
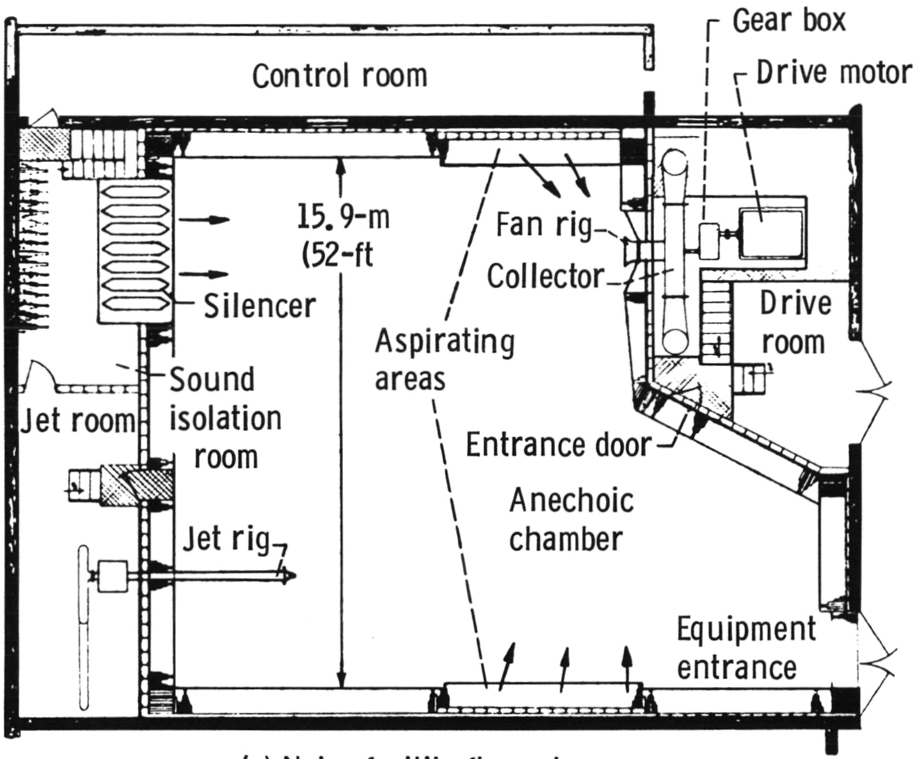
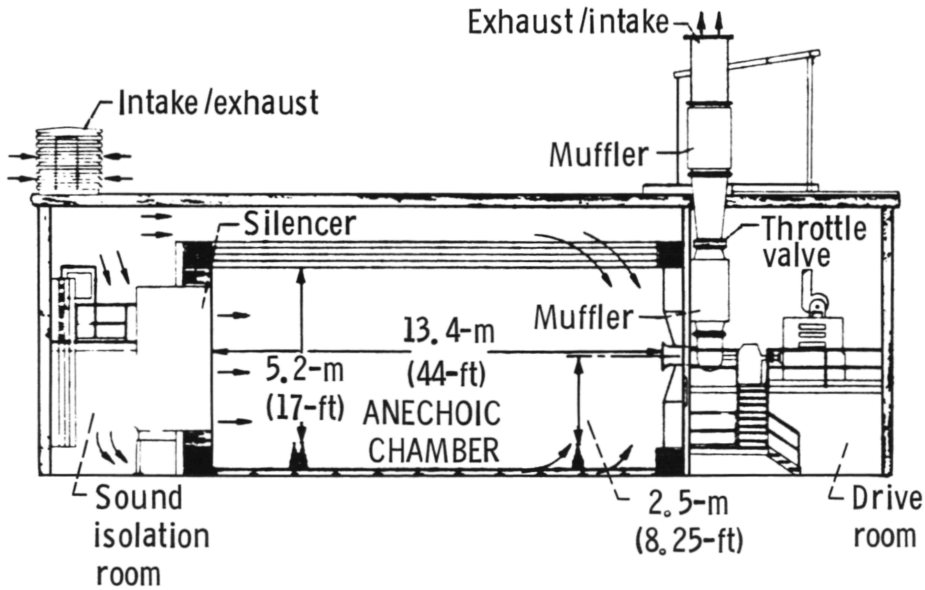


Figure 1. - Research fan installed in anechoic chamber.

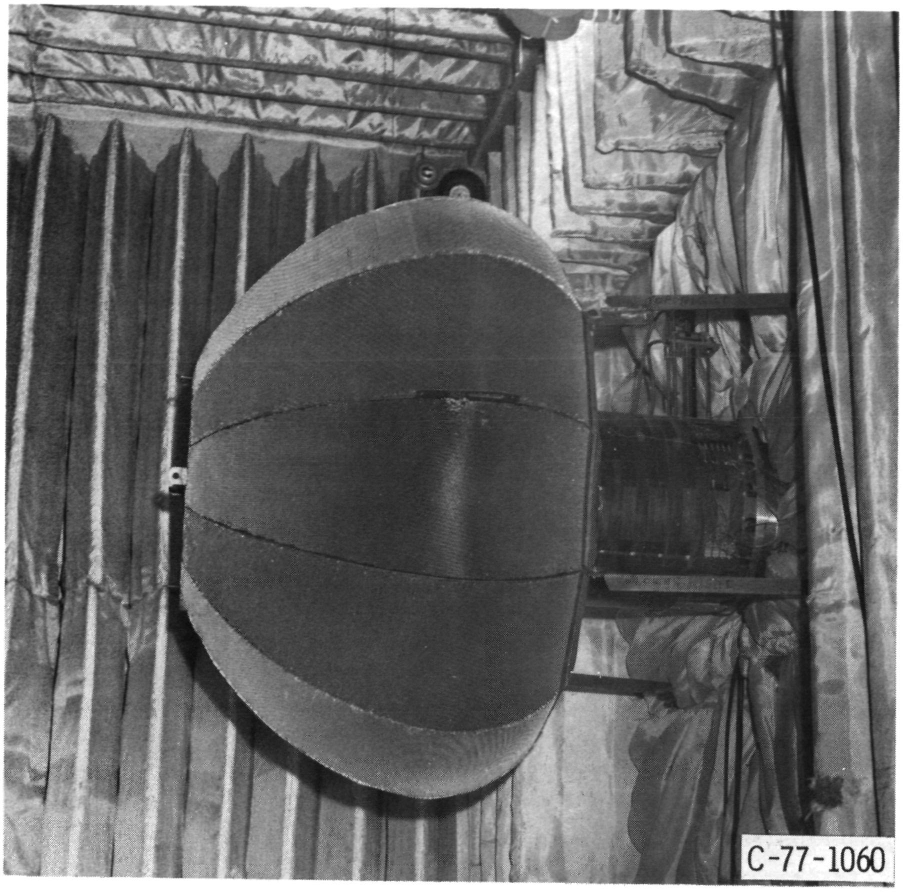


(a) Noise facility floor plan.

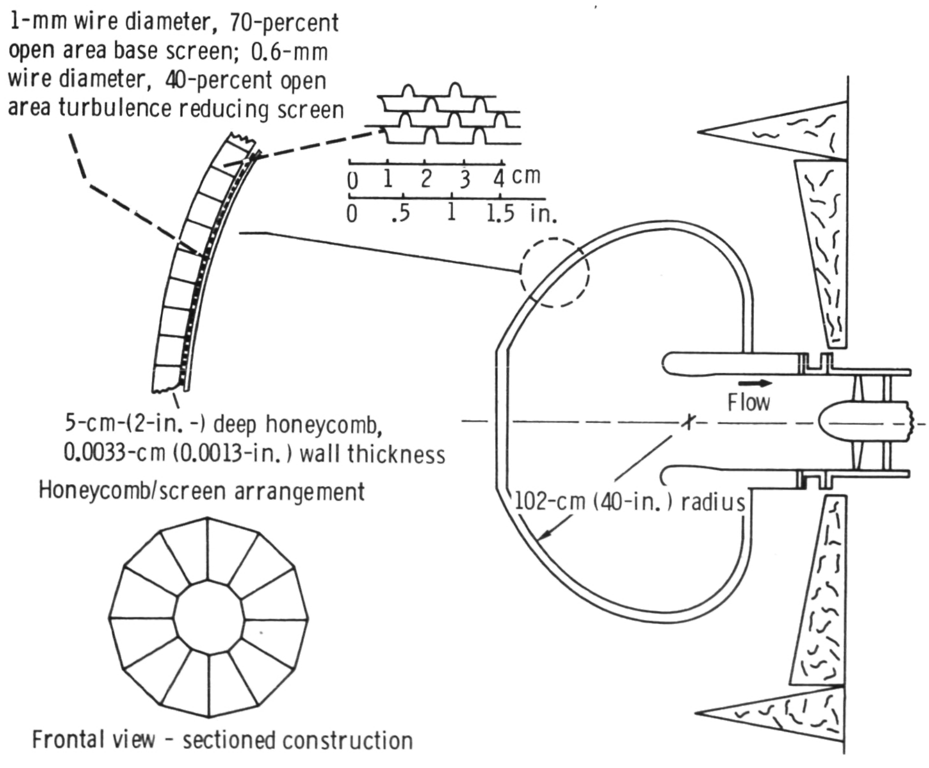


(b) Noise facility elevation view.

Figure 2. - Anechoic chamber.



(a) Installed on research fan in anechoic chamber.



(b) Cross section.

Figure 3. - Inlet flow control device.

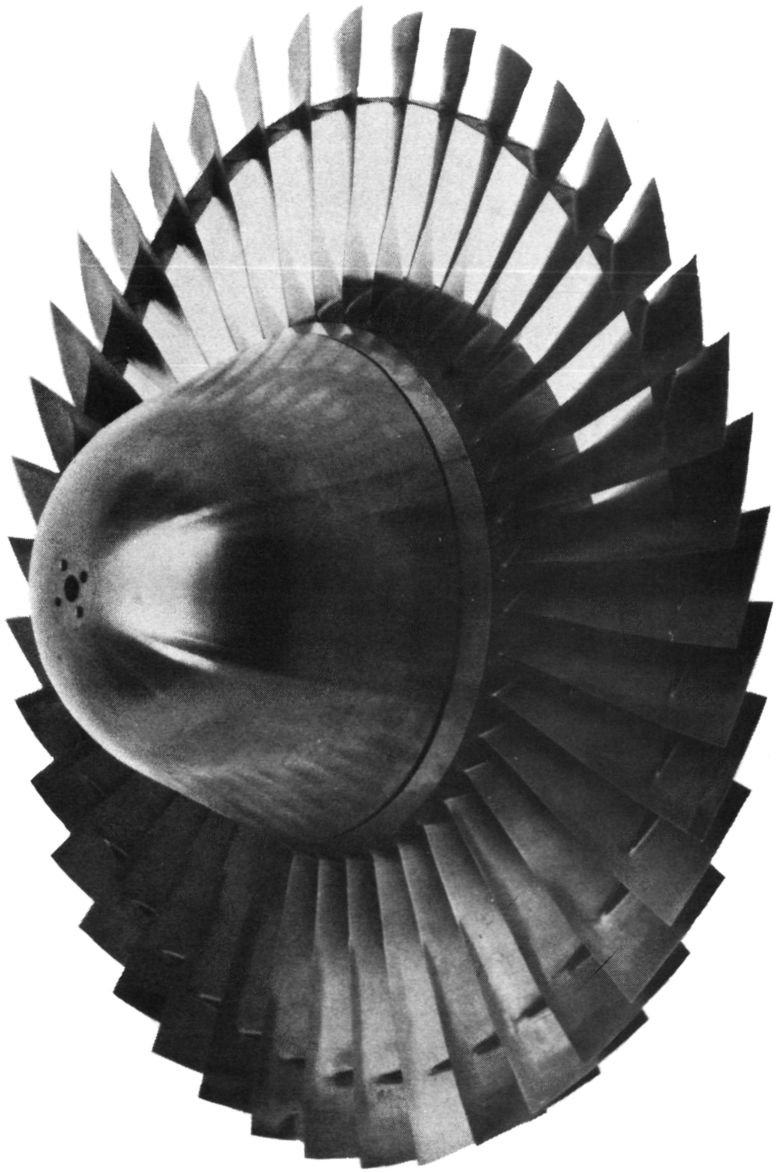


Figure 4. - QF-13 rotor viewed from upstream.

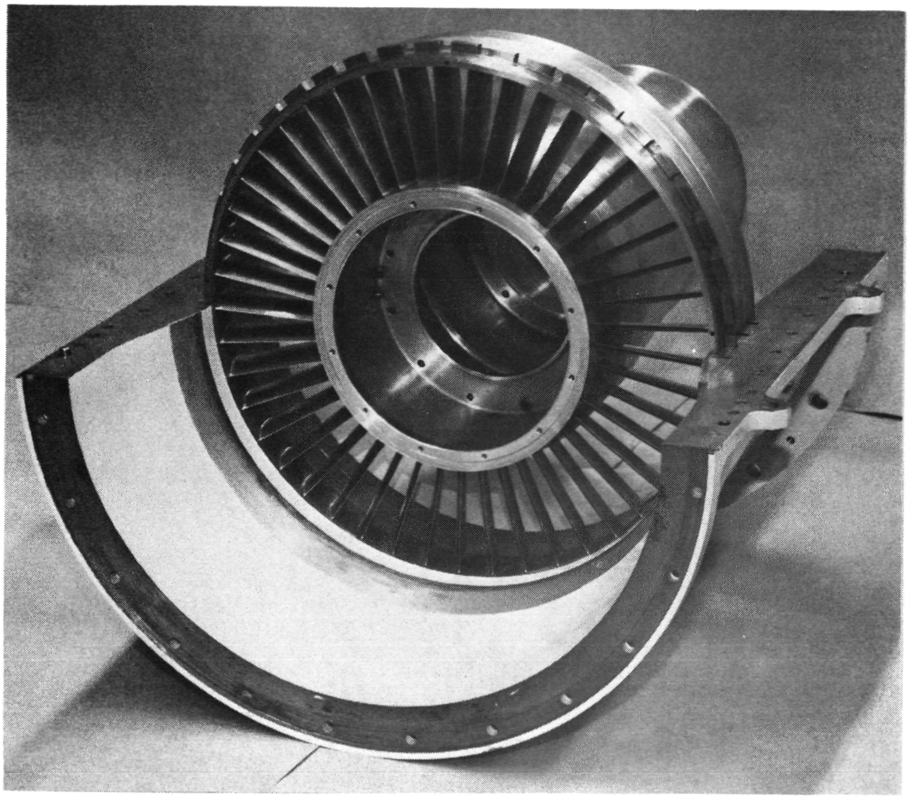


Figure 5. - QF-13 stator assembly viewed from upstream.

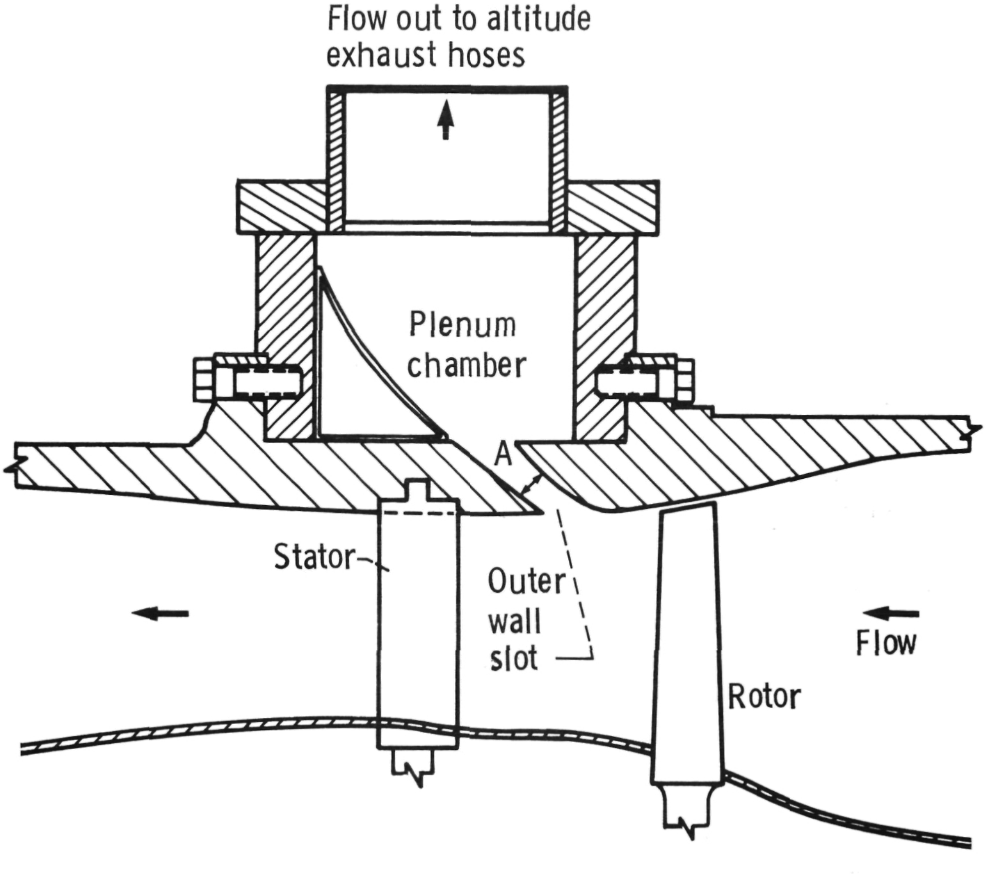


Figure 6. - Tip flow removal system. A ≅ 1.27 cm (.5 inch).

Figure 7. - Flow removal exhaust assembly.

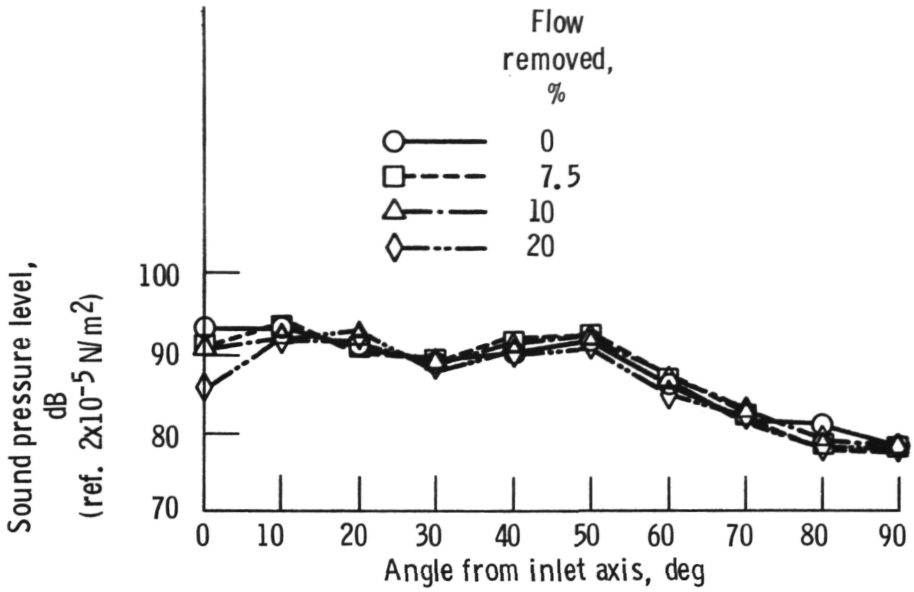


Figure 8. - Tone at blade passing frequency, 50% speed, with ICD installed.

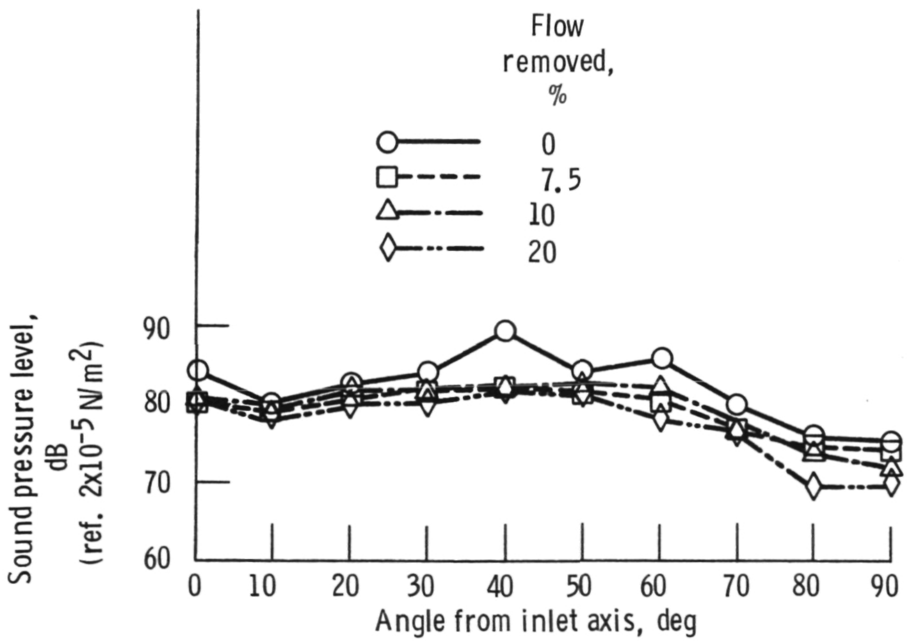


Figure 9. - Tone at twice blade passing frequency, 50% speed, with ICD installed.

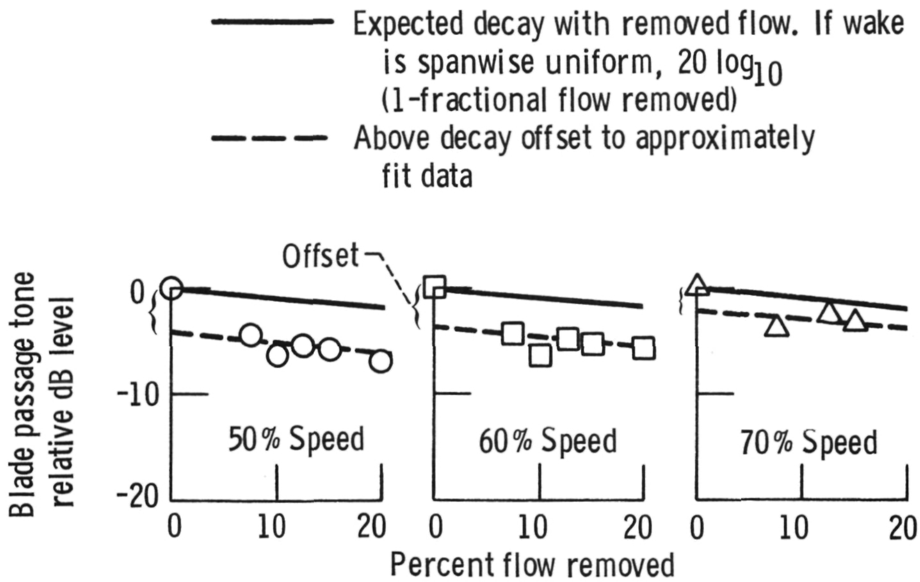


Figure 10. - Aft duct blade passage tone reduction.

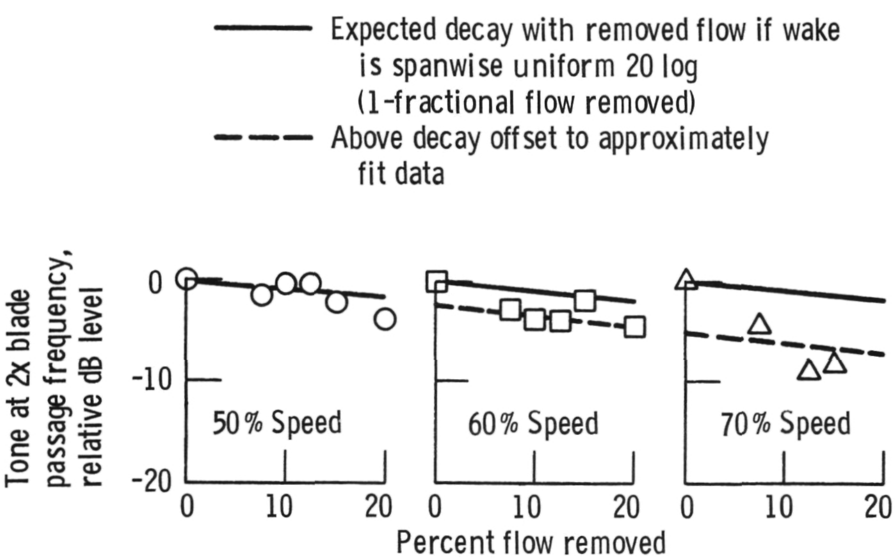


Figure 11. - Reduction of aft duct tone at twice blade passage frequency.

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16. Abstract

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